Identification of Transformer Core Vibrations and the Effect of Third Harmonic in the Electricity Grid

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Abstract—In this work, an experimental technique is applied for the measurements of the vibrations and deformation of a test transformer core. Since the grid voltage contains some higher harmonics, in addition to a purely sinusoidal magnetisation of the core the presence of third harmonic is also studied. The vibrations of the transformer core for points as well as the surface scan of the leg show more deformation in the corners of the leg than the middle of the leg. The influence of the higher harmonic of the magnetisation on the core deformation is also more significant in the corners of the leg. The core deformation shape under a sinusoidal magnetisation with a higher harmonic is more wavy and fluctuating than that under a purely sinusoidal magnetisation.

Keywords—Vibrations and noise, transformer, vibration measurements, laser vibrometer, higher harmonic.

I. Introduction

NOISE and vibrations of electrical machines and transformers have been the focus of many studies so far e.g. [1], [2]. In this work some results on the vibrations of transformers will be presented which are similar to those of electrical machines. In general noise generation is rather complex since it is caused by several sources. For instance, the assembly of the transformer and the mechanical structure directly affect the noise radiation. Considering the magnetic noise sources, they are mainly caused by the winding forces as well as the deformations of the core of the device. The windings noise is a result of the Lorentz force acting on the winding conductors and is proportional to the vector product of the magnetic induction and the current in the winding conductors. However, the deformation and vibrations of the transformer core, on which we focus in this work, are more complicated. Such deformation is caused by electromagnetic forces and magnetostriction in the core [3].

The contribution of the electromagnetic forces is often expressed as the effect of an external magnetic source on the magnetic material. However, magnetostriction deformation is a result of the interatomic interaction of the core material itself in the presence of a magnetic field. For a thorough explanation of these noise sources we refer to e.g. [1]. In fact both phenomena occur together and results in pulsating vibrations of the core. Based on the mechanical structure of the core, these vibrations cause audible acoustic noise.

The deformation and vibrations of transformer cores can be computed analytically by means of computational techniques [4]. However, in this work an experimental approach will be presented to measure the core vibrations by means of a laser technique. Moreover, the proposed technique provides us the possibility to visualise the core deformation. To this end, a test transformer core is made for the vibration measurements.

The grid voltage always contains some higher harmonics. Visualising the core deformation is especially useful to observe the effect of the higher harmonics present on the magnetisation voltage, which will be further explained.

The manuscript is organised as follows. In the next section the test transformer core will be described. Next the applied vibrations and deformation measurement technique will be presented. The measurement results under different magnetic excitation voltages will be given at the end, which will be followed by a discussion.

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II. Test transformer core

It has been previously reported that the assembly of a transformer core, i.e. the lap assembly, affects the flux path and may result in an extra noise and vibration source in addition to the aforementioned magnetic sources [3]. It is known that in the joint corners the flux travels from one lamination to another through the small air gap between the two in the out-of-plane direction. This in turn creates an attractive interlaminar force in the corners which results in a clamping noise. The aim of this work is to measure only the contribution of the magnetic forces and magnetostriction.

To this end, the transformer core designed for the vibrations measurement has no lap joint assemblies [5]. It is a simple single-phase transformer for which the laminations are cut in one piece. For the selection of the core material, a grain oriented electrical steel was not beneficial since such material is strongly isotropic. To this end, a nonoriented material type M350-50A was applied. This material has a thickness of 0.5mm and 3.50W/kg losses at 1.5T and 50Hz magnetisation. The laminations were cut by using the spark erosion technique to avoid any harm to the magnetic properties of the material due to the cutting. The core is 30cm×30cm with 5cm leg width. It is wound over three legs to spread the flux uniformly all over the core and avoid a local magnetisation. The fourth leg is left free for the vibration measurements, as shown in Fig. 1.

III. Laser scanning vibrometer

The vibrations of the test transformer core have been measured by using a laser scanning vibrometer. The scanner was a PSV-400 vibrometer Polytec laser. The scanner resolution has been adjusted for 0.2 mm/s/V. A magnetic excitation voltage is sent from a PC based program to an

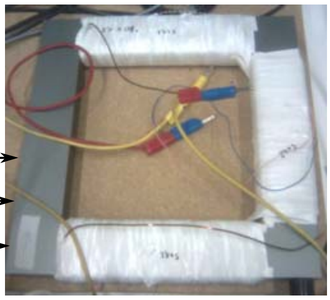

Fig. 1. Depiction of the single-phase test transformer core with only the primary excitation winding where one leg is left free for the vibration measurements.

amplifier and then sent to the excitation winding around the core. The applied voltage is adjusted to create the suitable magnetic induction in the core. Vibration of the core was then measured by the scanning vibrometer and post-processed to calculate the displacements. The laser measured the selected points of the core for preselected time intervals, based on an adjustment by the user, and then the average data of the measured velocities were saved. According to the average velocity signals, the deformation of the core was calculated.

In addition, the scanner can perform an automatic surface scan for a series of points in a grid pattern and display the results in a 3-dimensional (3D) animation. The scanner then probes the entire grid automatically using an interactive measurement grid. The results of this will be presented further on.

IV. Magnetic excitation voltage

In practice, the voltage waveform of the electrical power grid is not purely sinusoidal. There are always some higher harmonics present, which are caused by nonlinear voltage-current characteristics of the loads connected to the grid [6]. Looking at the industrial loads, power converters (rectifiers) and variable speed drives are well known examples of nonlinear loads. Previously, the effect of the third harmonic on the magnetostrictive behaviour of electrical steel has been reported [7]. The results showed the significant influence of the amplitude and especially the phase delay of the third harmonic on the magnetostriction strain harmonics. As a result, to study the effect of the higher harmonics, vibrations measurements of the core were performed under a purely sinusoidal applied magnetic voltage and a sinusoidal voltage with a third harmonic component. For that, combinations of the amplitude percentage and phase delay of the third harmonic, with respect to those of the fundamental, were applied.

V. Measurement results

To avoid any friction of the transformer core with the underlying surface, the core was hung from a frame in a horizontal plane parallel to the ground. In this way also the core weight is evenly distributed all over the plane, as shown in Fig. 2. The laser head was pointed at the free leg of the transformer. The deformation of the core was measured under a purely sinusoidal magnetic induction and a sinusoidal

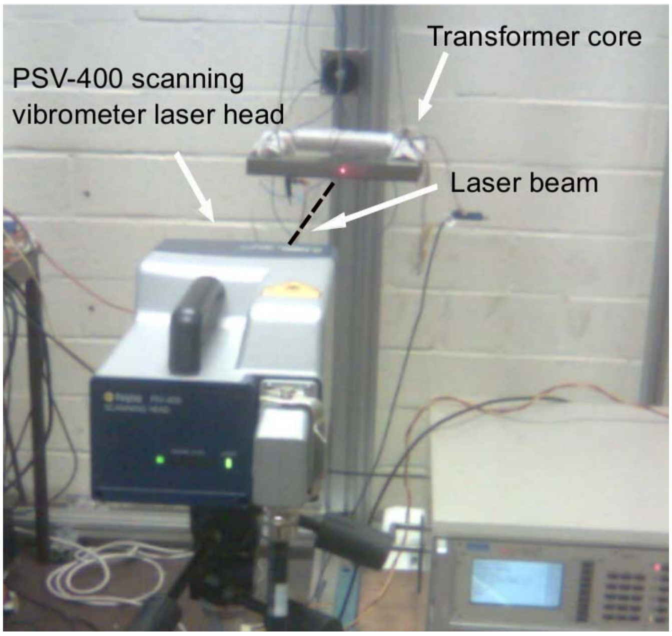

Fig. 2. The test transformer core placement for the vibrations and deformation measurements.

magnetic induction with a third harmonic component. For the measurements under the purely magnetisation the amplitude of the magnetic induction was assigned as 1.2T with a frequency of 50Hz. Such value corresponds to the knee of the B-H loop characteristic of the material, which is a common magnetisation level for transformers. For the measurements with a third harmonic component, the amplitude of the third harmonic was chosen as 6%, 8% and 10% with a phase delay of 0°, 90° and 180°, with respect to that of the fundamental. The deformation of three points along the free leg of the transformer core was measured, as shown in Fig. 1.

In transformers, the contribution of the magnetostriction to the deformation of the core is relatively significantly larger than that of the electromagnetic forces. The information about the odd harmonics is not relevant to the magnetostriction [8]. Looking at the even harmonics (for a 50Hz excitation) the 100Hz component has the largest magnitude. Thus, the 100Hz data of the measurement results under a purely sinusoidal magnetic induction with 1.2T amplitude and 50Hz are presented in Table I. Table II shows the 100Hz results for the combination of a sinusoidal magnetic induction with an amplitude of 1.2T and a frequency of 50Hz and a third harmonic with aforementioned amplitude ratios and phase delays.

TABLE I
The 100Hz magnitude [m] and phase spectrum [rad] displacement data of the selected points measured by the scanning laser vibrometer under a purely sinusoidal magnetic induction (B=1.2T and f=50Hz).

	point 1	point 2	point 3
Purely sine	3.80e-07$\angle -0.23$	2.070e-07$\angle -0.08$	1.300e-07$\angle -0.32$

TABLE II
THE 100HZ MAGNITUDE [M] AND PHASE SPECTRUM [RAD] DISPLACEMENT DATA OF THE SELECTED POINTS MEASURED BY THE SCANNING LASER VIBROMETER UNDER A SINUSOIDAL MAGNETIC INDUCTION (B=1.2T AND f=50HZ) WITH A THIRD HARMONIC COMPONENT WITH 6%, 8% AND 10% AMPLITUDE RATIOS AND 0°, 90° AND 180° PHASE DELAYS, WITH RESPECT TO THAT OF THE FUNDAMENTAL.

6% third harmonic			
phase delay	point 1	point 2	point 3
0°	3.49e-07∠0.16	1.82e-07∠0.34	1.28e-07∠−0.31
90°	3.36e-07∠−0.61	1.97e-07∠−0.37	1.31e-07∠−1.39
180°	3.31e-07∠2.80	1.96e-07∠0.55	1.20e-07∠−1.61
8% third harmonic			
phase delay	point 1	point 2	point 3
0°	3.55e-07∠0.19	1.77e-07∠0.05	1.27e-07∠−0.37
90°	3.39e-07∠0.16	1.79e-07∠0.06	1.32e-07∠−0.31
180°	3.25e-07∠−0.89	1.91e-07∠−0.75	1.27e-07∠−1.62
10% third harmonic			
phase delay	point 1	point 2	point 3
0°	3.59e-07∠0.16	1.92e-07∠0.00	1.28e-07∠−0.09
90°	3.38e-07∠−0.12	1.74e-07∠−0.12	1.33e-07∠−1.24
180°	3.22e-07∠2.27	1.76e-07∠1.48	1.24e-07∠2.08

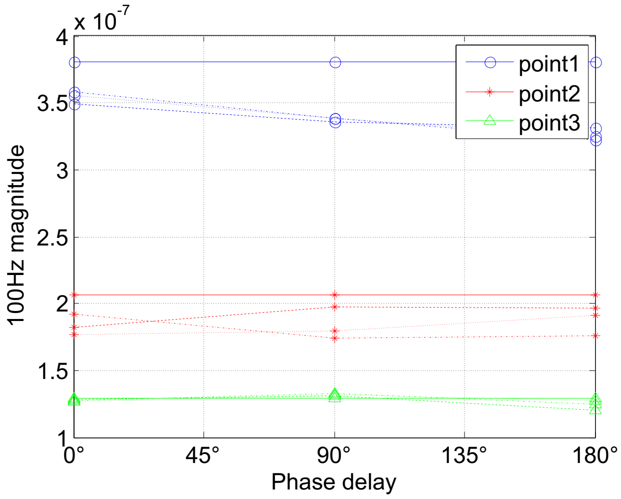

Fig. 3. The 100Hz magnitude [m] of the selected points measured by the scanning laser vibrometer under a purely sinusoidal magnetic induction (B=1.2T and f=50Hz) and a sinusoidal magnetic induction with a third harmonic component with 6%, 8% and 10% amplitude ratios and 0°, 90° and 180° phase delays with respect to that of the fundamental.

VI. Results Discussion

A. Deformation of Points

The measurement results under a purely sinusoidal magnetic induction shows that the core deforms more in the corner of the leg than in the middle. The influence of the third harmonic on the deformation of the core is larger in point 1 than point 2 and point 3, respectively. This is shown in Fig.3, in which the 100Hz magnitude of the deformations of the points are plotted versus the phase delay of the third harmonic. The blue lines with circle marker (the four top lines) represent the deformation of point 1. The red line with asterisk marker (the four middle lines) show the deformation of point 2, which are all smaller than those of point 1. The green line with upward-pointing triangles (the four bottom lines) show the deformation of point 3, which are all smaller than those of point 2. For each point, the solid line is the deformation under the purely sinusoidal magnetisation. The dashed, dotted and dashed-dotted lines show the deformations under 6%, 8% and 10% third harmonics, respectively.

B. 3D Animation of the Core Leg Deformation

To clearly see the deformation, a 3D animation of the free leg of the core is made. For a purely sinusoidal magnetisation of the core, two pictures of the animation of the core free leg surface are shown in Fig.4, where the maximum (the top picture) and the minimum (the bottom picture) deformations are presented. It is observed that in fact the core free leg does not deform uniformly all over the surface but more in the corners. The effect of the third harmonic can be illustrated also more clearly with a 3D animation. Fig. 5 shows three pictures of the free leg deformation animations under 6% third harmonic with the aforementioned phase delays from the top to the bottom corresponding to 0°, 90° and 180° phase delays, respectively. Based on Fig. 5 and Fig. 4, two main

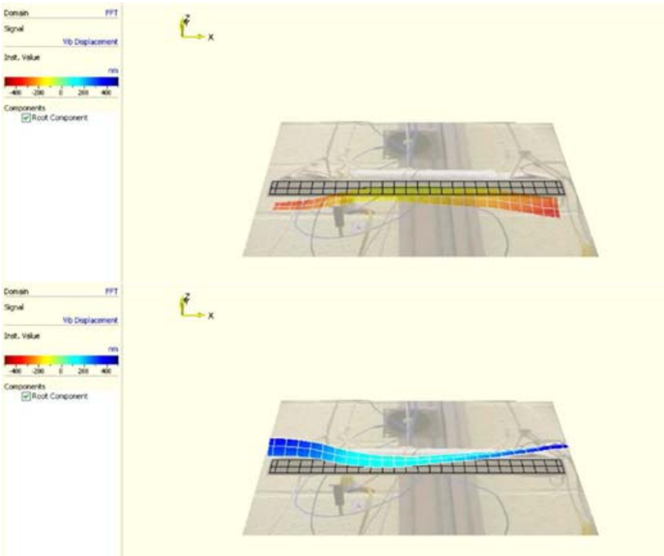

Fig. 4. A 3D vibration measurement of the free leg of the single-phase test transformer core under a purely sinusoidal magnetic induction with 1.2T amplitude and 50Hz representing the maximum (inward) and the minimum (outward) deformations from the top to the bottom, respectively.

observations can be pointed out. All three measurements under a magnetisation with a third harmonic, compared with that under a purely sinusoidal, show a more wavy deformation of the free leg surface. In Fig. 4 the surface deforms more or less in a quadratic shape. However, the surface deformation in Fig. 5 shows some fluctuations in a sinusoidal shape in addition to the main quadratic deformation. Moreover, we can observe in the same figure that the larger the phase delay of the third harmonic, the larger the fluctuations. For the case of 0° phase delay the fluctuations are at the leg corners. However, going to 90° phase delay they grow more along the leg. In the case of 180° phase delay the whole leg undergoes a sinusoidal deformation. We can conclude that to consider the influence

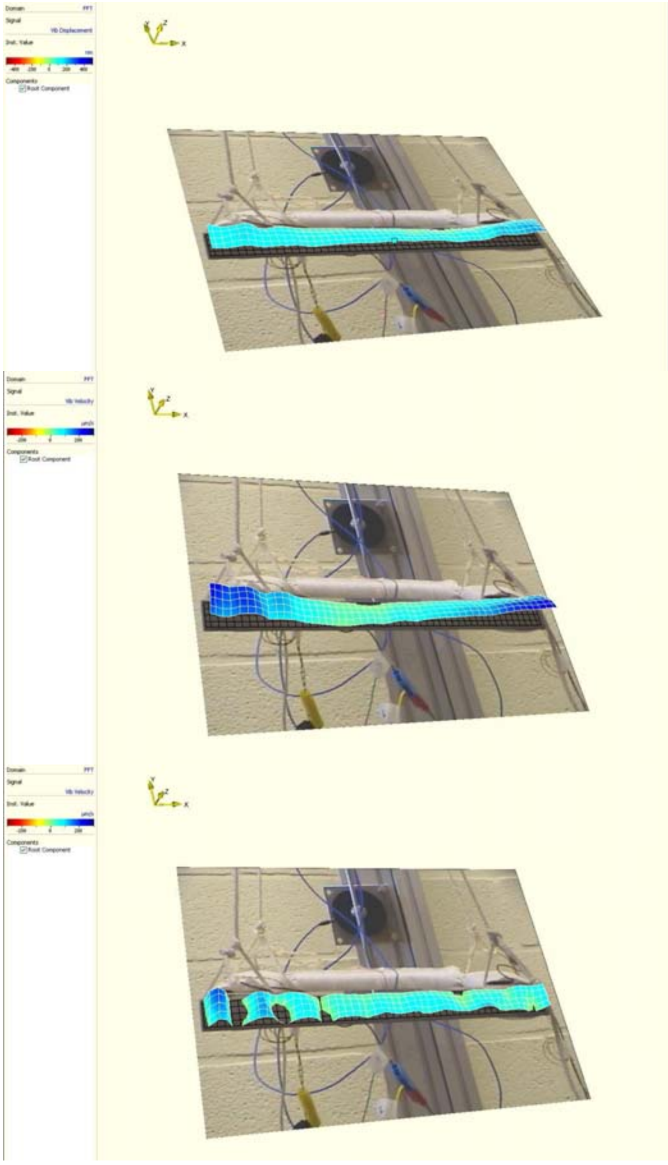

Fig. 5. A 3D vibration measurement of the free leg of the single-phase test transformer core under a sinusoidal magnetic induction with a fundamental harmonic of 1.2T amplitude and 50Hz and a third harmonic with 6% amplitude and 0°, 90° and 180° phase delays from the top to the bottom, respectively.

of the higher harmonics in the grid on the deformation of transformer core, both the amplitude and the phase delay of the higher harmonic, with respect to the fundamental, play a significant role.

VII. Conclusion

In this paper the vibrations and deformation of a test transformer core are measured by means of a laser scanning vibrometer. Such deformation are caused by the magnetic forces and magnetostriction in the core, which occur simultaneously. Since the grid voltage is never purely sinusoidal, the measurements are performed under a sinusoidal magnetisation with a third harmonic and compared with those under a purely sinusoidal magnetisation. In addition to the point measurements an animation of the core deformation is also visualised. The results show that in all cases the core deforms more in the corner than in the middle. For the sinusoidal magnetisation with a third harmonic the leg deformation shape is more complex than that under a purely sinusoidal magnetisation. We may conclude that to consider the influence of the higher harmonics in the grid on the deformation of transformer core, both the amplitude and the phase delay of the higher harmonic should be taken into account.

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